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ABSTRACT

Capacity control for heat pump (HP) systems is essential to efficiently meet variable heating loads in domestic buildings. A low-to-medium temperature hot water supply within a 30 ºC-55 ºC range is commonly required for domestic heating load applications. In this study, the performance of a variable speed air source heat pump (ASHP) system was studied in the laboratory under a series of ambient conditions at -2 ºC, 2 ºC, 7 ºC and 15ºC, examining performance at different water supplying temperatures (WST) of 30 ºC, 35 ºC, 40 ºC, 45 ºC, 50 ºC, and 55 ºC. The performance of the variable speed HP system was evaluated in a conditioning chamber at the above-mentioned ambient temperatures and corresponding humidity levels as per BS EN 14511 standards. The HP performance at six different heating capacities of 18kW, 15kW,12kW, 9kW, 6kW, and 3kW was measured and evaluated via co-efficient of performance (CoP) values. The CoP values changes according to the load, water supply temperature (WST) and ambient temperature conditions. The CoP values for fixed ambient temperature conditions and WST i.e., 7 ºC and WST 30 ºC (7A30W) at 15kW, 12kW, 9kW, 6kW, and 3kW were found to be 3.56, 3.83,4.35, 4.19, and 3.39, respectively. The corresponding frequency of operation was 112.25Hz, 105.87Hz, 81.57Hz, 61.05Hz, 37.64Hz, 18.75 Hz with an absolute percentage difference of 87.01%, 76.45%, 35.95%, 1.75%, 37.26%, and 68.75% to that of the nominal frequency of 60Hz. The trend was similar by changing WST to 35 ºC, 40 ºC, 45 ºC, 50 ºC and 55 ºC, but with lower CoP values and a smaller variation range. The difference between water inlet and supply temperature (delta T) is another important parameter in domestic heat load applications, and this study also presents results of comparative testing of delta T of 5, 10 and 20 at ambient conditions of 15 ºC for WST of 40 ºC, 45 ºC, 50 ºC, and 55 ºC. The experimental results indicate that this variable speed-based HP system has the potential to meet different domestic heating demands within a range of WST and ambient conditions.

1. INTRODUCTION

Domestic building sector in United Kingdom (UK) consumes 29% of the total final energy consumption (Energy Consumption report, 2017). A major part of the domestic building energy consumption (79%) is because of space heating (SH) and domestic hot water (DHW) production, while cooking, lighting and other appliances consume the rest (Druckman and Jackson, 2008). UK target as committed in Climate Change Act, 2008 is to reduce carbon emissions by 80% to that of 1990 levels by 2050 (Climate Change Act, 2008). Hence, there is a great potential of CO_2 emission reduction if the domestic building heating demand could be meet by renewable energy-based energy devices like heat pump instead of fossil fuel-based gas/oil boilers.
The ASHP heating device utilizes environmental thermal heat energy from the air, with proportion of electrical energy mainly for the compressor operation. In seeking a system which can modulate its capacity according to the load requirements and operate over a wide range, a variable speed compressor-based HP system is a viable option. The performance of ASHP system depends on the ambient temperature conditions, WST, and the heating capacity. Energy efficiency is improved using variable speed compressor due to capacity match at different part loads, resulting in reduced cycling losses. The current standard BS EN14511 classify the HP system depending on the WST, as low temperature (35 ºC), medium temperature (45 ºC), high temperature (55 ºC), and very high temperature (above 65 ºC) (BS EN14511, 2004). The performance assessment of the variable speed compressor-

based HP system at different heating capacities, heat supply temperature, ambient conditions require investigation for potential improvement in performance. Hence the HP development, testing under the controlled laboratory conditions through experimental analysis becomes very crucial to see the system actual performance.

1.1 Literature Review

The control of the system at part loads conditions basically differentiates variable speed drive from the conventual fixed speed HP system. Higher CoP values, faster temperature control, low starting current, noise, vibrations, and more control were found well-established advantages of variable speed HP (Qureshi and Tassou, 1996). However, there were certain issues reported, i.e., impact of variable speed operation on the isentropic and volumetric efficiency of the compressor, pressure ratio (Pr) and inverter losses. The CoP of ASHP has been reported to be in the range of 3.2-4.5, according to lab scale tests as per EN14511 test standards at 2A35W (Bundesamt *et al*., 2016). The earlier studies on the variable speed compressor HP system for performance improvement, associated issues, volumetric and isentropic efficiency is discussed with research gaps in the following.

The inverter losses due to change in compressor supplied frequency was analysed experimentally for ground source heat pump (GSHP) while keeping constant load/source side temperature of 26 ºC/4.5 ºC by (Madani *et al*., 2010). The results showed that overall, 30% reduction in CoP values was noticed according to the frequency of operation. The experiments were conducted at single WST with frequency variation in the range of 30Hz-90Hz. The isentropic efficiency was highest when the compressor frequency was near to the nominal value of 50 Hz. ASHP system with nominal capacity of 9.8kW at -5 ºC was developed for retrofitting applications and tested the performance at a single WST of 60 ºC, different ambient conditions as per test standard BS EN14511 (Quinn, 2012). The frequency modulation range was established experimentally in between 37.5 Hz-75 Hz for the safe compressor operation. The HP was tested at four fixed frequencies of 37.5 Hz, 50Hz, 60Hz, and 75 Hz using off the shelf inverter. The heating capacity variation range was 3.14-4.87kW, 3.4-5.38kW, 3.43-5.57kW, 3.49-5.86kW, 3.59-6.03kW, 3.73-6.597kW due to frequency modulation range (37.5-75 Hz) for fixed ambient temperature conditions of -15 ºC, -7 ºC, -2 ºC, 2 ºC, 7 ºC, and 15 ºC, respectively. The highest performance was recorded at the system nominal frequency of 60Hz, while keeping other conditions constant. However, the speed modulation range was very limited with single WST. Variable speed ASHP system was experimentally studied for the performance evaluation in the conditioning chamber for various WST of 35 ºC, 45 ºC, 50 ºC at ambient temperature conditions range of -15 ºC to 7 ºC without controlling the heating capacity at constant value (Hewitt *et al*., 2011). The water mass flow rate was fixed with no control over delta T. The CoP value increased from 2.43 to 4.26 depending on the operating frequency and the ambient temperature variation was in between -15 ºC and 7 ºC at fixed WST of 35 ºC. At higher WST of 50 ºC the same trend of increase in performance has been shown with increase in ambient temperature but with the CoP value of 1.73 & 3.15 at -15 ºC and 7 ºC respectively, which is 40.46%, 35.23% lower than that of 35 ºC. Capacity control ground source heat pump (GSHP) was investigated with an aim to increase the system efficiency with the variable speed compressor, fan, water circulating pumps, where two different prototypes were tested and investigated under the laboratory conditions (Karlsson, 2007). It was reported that the thermal inertia of various hydronic heating distribution system (underfloor, hydronic fan coil, and radiator) influences the cyclic properties of heat pump for space heating. The cycling characteristics has less effect while using variable speed heat pump system due to load matching and at same time the temperature of water inside the system was maintained at set-point more precisely. It was found that the response time at start-up was also affected by thermal inertia of heat distribution type, in addition to the system configuration, the way it was linked to hot water supply temperature (Karlsson and Fahlen, 2008). It was concluded that the water supply and entering water temperature in addition to the difference between these two value effects the seasonal performances significantly. The reduction in water supply/return temperature values from 55/45 ºC to 35/28 ºC results in increasing seasonal performance by 30-35%. The performance improvement was because of the reduction in WST and the impact of delta T value variation was not considered. Another experimental study on the variable speed compressor with application for industrial plant cold storage was conducted to investigate the energy saving potential (Aprea *et al*., 2009). An increase in energy saving of up to 20% was reported for various conditions while using the variable speed control in comparison to the thermostatic control. The study conducted for finding the optimal frequency while maintaining the required cold storage temperature, by keeping evaporating, condensing temperature, and heat load constant. The system frequency was varied for power saving by matching the load demand and comparing the results with that of nominal frequency of 50Hz. The HP system was evaluated at WST of 34°C & 42°C and approximately 30% of energy saving could be achieved at frequency of 24 Hz and 36 Hz satisfying the loads at set conditions, compared to that nominal frequency.

The study investigating the variable speed compressor isentropic, & volumetric efficiencies, inverter losses, pressure ratio (Pr) at different frequency of 35 Hz, 40 Hz, 50 Hz, 60 Hz and 75Hz was conducted (Cuevas and Lebrun, 2009). It was concluded that the compressor efficiencies were mainly dependent on the pressor ratio (Pr) and effected very slightly with the compressor supplied frequency except for the tests of 40 Hz and 75Hz and the reason was linked to lubrication issue and other electromechanical losses at low and high-speed operation. The maximum isentropic efficiency was 65% when the pressure ratio was 2.2, while the volumetric efficiency showed linear decrease from 98% to 83% with increase of pressure ratio from 1.5 to 5.6.

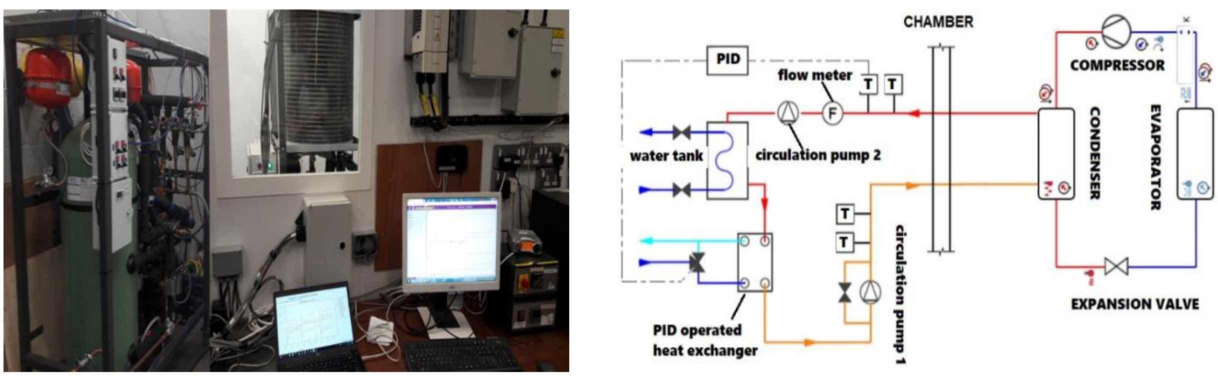
1.2 Present Work Contribution

The above literature review on the variable speed HP sytem shows that the focus of the studies were on individual component(i.e compressor isentropic and volumetric efficiencies, inverter losses), single water supply and return temperature, uncontrolled delta T values. The variable speed heat pump system for the of fixed heating capcities simulating the real domestic heat load demand, WST, and ambient conditions under the lab conditions is missing from the literature, to the best of author's knowledge. Therfore in this study variable speed ASHP prototype developed and tested as per EN14511-3 (EN 14511–3, 2004) method at various steady state heating capacity, WST, and ambient conditions to evaluate the performance of the system for the domestic heat load applications. The establishment of the optimal operating point and the possibility for potential energy saving, needs detailed experimental results analysis, which could provides information for further performance predictions.

2. METHODOLOGY

2.1 Test Facility

The test facility mainly includes the developed ASHP system, conditioning chamber, heat source, and load side arrangements. The experimental setup/ test facility with schematic diagram is shown in Fig. 1(a, b). It could provide range of ambient conditions on source side and different water supply/entering temperature using PID controlled valves in combination to the water flow rates adjustment via variable speed water circulation pump. The delta T value, difference between WST and entering water temperature (EWT), is controlled by PID valve on the load side. As can be seen from schematic diagram the heat load is dumped to the water tank and/or heat exchanger via fresh water supply. The PID valve, which open and closes according to the temperature set points for managing delta T.



(a) (b)

Figure 1: a) Experimental setup, b) Simplified schematic diagram for the HP inside the conditioning chamber and heat load dumping rig

Proper measurement, data loggers and the control mechanism setup were established. The uncertainty associated with the measurement devices is shown in Table 1. Variable speed scroll compressor model number XPV0302E-4X9 and controller was provided by Emerson Climate Technologies (Copeland Ltd). The controller (SEC) developed for XPV/XHV Copeland variable speed scroll families for heating and cooling applications, provide the speed control for compressor operation.

Table 1: Uncertainties ranges for measurement instruments

Measured quantity	**Measurement device**	**Units**	**Uncertainties**
Temperature	Inline and Surface PT100, Eltek GD 24	^oC	±0.3
Liquid mass flow rate	Electromagnetic, Eltek, GC 62	kg/s	±1.5 %
Electric power consumption meter	Landis and Gr P350	kW	± 1 %
Compressor speed	XPV0302E-4X9	rpm	± 0.5 %
Refrigerant Pressure	PT5 Pressure transmitters	kPa	± 1 %
Refrigerant Temperature	NTC (ECN-EG30)	^oC	± 0.5

2.2 Testing Method

The testing procedure for ASHP system mentioned in EN14511-3, 2004 have been followed in terms of methodology, sensor, quantity, & measurement accuracy requirements. The ambient conditions in the conditioning chamber for the testing was maintained with PID controlled heater, cooler & humidifier at test conditions of -2 ^oC, 2 ^oC, 7 ^oC & 15 ^oC. The PID humidifiers was able to meet the requirements mentioned in the standard for the relative humidity (RH) upper limits and lower limits. On heat source side inside the conditioning chamber the ambient temperature and humidity was maintained as per standard requirements with heater, cooler and steamers controlled by the PIDs. Two separate PIDS controlling the heater, cooler independently was keeping the set point temperature inside the conditioning chamber. Similarly, two steamers controlled by the PIDs were operating to maintain the required humidity requirements. The set point values for water supply temperature, ambient temperature, humidity was controlled with high accuracy. Four different ambient conditions with varying water supply temperature (WST), and various delta T values have been chosen to investigate the system for low to medium WST applications of 35 ^oC to 55 ^oC. The tested conditions ambient temperature, humidity, and WST values is shown in Table 2. Although, delta T values mentioned in the standard was 5, which has been followed and extended to 10 and 20 to see the impact on the HP performance. The delta T values have application for system performance improvement and radiators are designed in the range of 10 ^oC - 20 ^oC value.

Table 2: HP lab testing conditions

HC (kW)	**T_a (^oC)**	**RH (%)**	**RH (%) - upper limit**	**RH (%)- lower limit**	**WST (^oC)**	**delta T**
12,9,6,3	-2	79.3	85.5	73.2	35, 45	10
12,9,6,3	2	83.9	88.7	79.1	35, 45, 55	10
15,12,9,6,3	7	86.9	90.8	83	30, 35, 40,45, 50,55	10
18,15,12,9,6,3	15	90	93	87.1	30, 35, 40,45, 50, 55	10
18,15,12,9,6,3	15	90	93	87.1	25, 30, 35, 40,45, 50,55	5
18,15,12,9,6,3	15	90	93	87.1	40, 45, 50,55	20

The superheat set point was 10 K during all the tests and it was maintained by using electronic expansion valve model number EXL-BF1-Unipolar stepper motor valve. The controller was controlling the superheat value according to the set point and whenever there was an abrupt change on the heat supply load side due to this PID controlled valve opening or closing then the controller responded mainly by changing the superheat to the new load conditions. The heating capacity on the water side of condenser was balanced to that of the refrigerant side. The energy balance analysis was performed to see the reliability of experimental results as shown in Fig. 2. On water side of the condenser the heating capacity was calculated with equation (1) using measured water inlet and outlet temperature difference, the water specific heat and mass flow rate. The refrigerant mass flow rate through the condenser and evaporator was measured through the flow meter installed in the liquid refrigerant line. The heating capacity on refrigerant side was calculated by equation (2) using the measured values of the refrigerant mass flow rate and the enthalpy difference between the inlet and outlet of the condenser.

$$Q_w = \dot{m_w}\ C_P \Delta T \tag{1}$$

$$Q_r = \dot{m}_r \Delta h \tag{2}$$

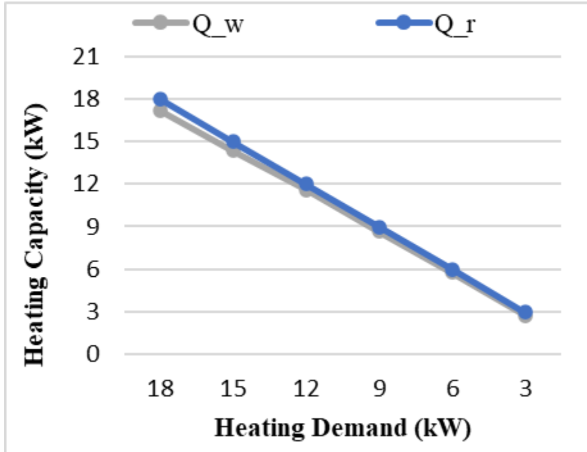


Figure 2: Energy balance between refrigerant and water side of condenser

Following the energy balance analysis, all other tests were completed, and the results are presented in the following section. The tests results were repeated to maintain the accuracy and errors limits. The CoP, ratio between the heat output and total electric power consumption was calculated by equation (3);

$$CoP = \frac{Q}{P_{total}} = \frac{C_p * \dot{m}_w * \Delta T}{p_{comp} + p_{aux}} \tag{3}$$

whereas Q is heating capacity, P is the electric power consumption, c_p the water specific heat, $\dot{m}$ is water mass flow rate (kg/s), and ΔT is the difference between the water supply temperature (WST) and entering water temperature (EWT).

3. RESULTS

The modulation range for the compressor was in between 15-120Hz. The summary results for HP performance under the conditions of ambient temperature at 15 ºC, 7 ºC, 2 ºC and -2 ºC, with (WST) of 35 ºC, 45 ºC, 55 ºC for different heating capacity is presented in Table 3. The operation of the system at nominal frequency of 60Hz shows good performance compared to its operation above/ below to that of the nominal value while keeping other conditions fixed. The nominal frequency of 60Hz for a fixed WST and ambient conditions results in higher CoP values, was mainly because of higher compressor isentropic efficiencies, lower-pressure ratio. Notation used in the table, i.e. 15A35W represent the ambient temperature being 15 ºC and WST of 35 ºC. The HP works at a wide range of changing pressure ratio and only at single nominal operating point, external pressure ratio is equal to that of compressor internal pressure ratio. At all other points under/ over compression results in smaller efficiency.
Fig. 3 (a, b, c, d) shows CoP trends against the constant heating capacities at ambient conditions of 15 ºC, 7 ºC, 2 ºC & -2 ºC, respectively. At ambient conditions of 7 ºC, test for 18kW heating demand was conducted but the heating capacities achieved were slightly lower than 18kW and therefore not presented. At 2 ºC & -2 ºC, 15kW tests were not possible due to conditioning chamber limitations and a maximum heating capacity achieved were of the order of 12kW. The CoP values for the fixed heating capacities depends on the ambient conditions, and WST. The CoP values for 18kW,15kW, 12kW, 9kW, 6kW, 3kW varied in the range of 3.91-2.63, 4.72-2.78, 5.34-2.87, 5.31-2.94, 5.23-2.83, 4.01-2.18 for a WST variation between 30 ºC & 55 ºC at ambient conditions of 15 ºC (Fig. 3, a). At 7 ºC (Fig. 3b), the CoP values for each heating capacities of 15kW, 12kW, 9kW, 6kW, 3kW variation range is 3.56-2.43, 3.83-2.43, 4.35-2.41, 4.19-2.43, 3.39-2.28 for a WST variation between 30 to 55 ºC. The CoP values with 12kW, 9kW,6kW, 3kW with WST of 35 ºC- 55 ºC are in the range of 3.04-2.21, 3.43-2.21, 3.29-2.22, 2.79-2.14 respectively at 2 ºC (Fig. 3., c). At low ambient conditions of -2 ºC, tests for 55 ºC WST was not possible with 12kW, and 3kW due to higher discharge line temperature (DLT) limitations of 120 ºC. Fig. 4 (a, b, c, d) depicts the frequency variation against the fixed heat heating capacities for the range of WST at four ambient temperature conditions of 15 ºC, 7 ºC, 2 ºC & -2 ºC, respectively. The frequency requirements increase with increase in heating capacity while keeping the WST and ambient temperature conditions fixed.

Table 3: Summary results for the heat pump (HP) test

EWT/WST	**HD (kW)**	**HC (kW)**	$\dot{m}_w$ **(kg/s)**	**RH (%)**	**T_a (ºC)**	**Φ (Hz)**	**Pr**	**P(kW)**	**COP**
	15A35W								
25/35	18	17.97	0.43	90.25	14.91	101.35	3.62	4.94	3.64
25/35	15	14.98	0.36	89.70	15.16	93.10	3.48	3.65	4.11
25/35	12	11.98	0.29	91.18	15.19	62.87	2.71	2.42	4.96
25/35	9	8.98	0.22	91.87	14.95	45.60	2.50	1.88	4.78
25/35	6	5.98	0.14	89.34	15.11	30.04	2.39	1.29	4.64
25/35	3	2.98	0.07	91.47	14.92	15.21	2.33	0.85	3.50
	15A45W								
35/45	18	17.98	0.43	90.99	15.25	112.58	4.16	5.72	3.14
35/45	15	14.98	0.36	90.12	14.87	97.02	3.87	4.37	3.43
35/45	12	11.98	0.29	91.54	14.87	65.27	3.46	3.13	3.83
35/45	9	8.98	0.22	90.56	14.88	47.46	3.26	2.40	3.75
35/45	6	5.98	0.14	89.27	14.88	30.99	3.06	1.64	3.65
35/45	3	2.98	0.07	91.54	14.87	15.52	3.08	1.11	2.68
	15A55W								
45/55	18	17.97	0.43	92.61	14.92	114.23	4.95	6.84	2.63
45/55	15	14.98	0.36	91.23	14.81	97.42	4.73	5.39	2.78
45/55	12	11.98	0.29	89.82	14.43	68.64	4.50	4.18	2.87
45/55	9	8.98	0.22	91.10	14.61	50.52	4.26	3.06	2.94
45/55	6	5.98	0.14	89.92	14.80	32.49	3.95	2.11	2.83
45/55	3	3.00	0.07	91.78	14.89	15.97	3.93	1.38	2.18
	7A35W								
25/35	15	14.95	0.36	89.14	6.90	107.69	4.53	4.80	3.12
25/35	12	11.98	0.29	88.37	6.82	85.27	4.14	3.57	3.35
25/35	9	8.98	0.22	87.85	6.76	58.77	3.47	2.34	3.84
25/35	6	5.98	0.14	87.91	6.79	37.78	3.19	1.57	3.80
25/35	3	2.98	0.07	87.77	7.32	21.73	3.69	1.06	2.81
	7A45W								
35/45	15	14.98	0.36	88.07	6.82	108.33	5.42	5.56	2.64
35/45	12	11.99	0.29	88.22	7.71	88.50	5.32	4.34	2.76
35/45	9	8.99	0.22	88.42	6.86	59.69	4.43	2.89	3.11
35/45	6	5.98	0.14	88.68	6.83	38.95	4.15	1.96	3.05
35/45	3	2.98	0.07	88.81	6.95	19.15	4.02	1.23	2.43
	7A55W								
45/55	15	14.97	0.36	87.97	7.62	110.90	5.93	6.17	2.43
45/55	12	11.98	0.29	87.32	7.08	89.69	5.90	4.93	2.43
45/55	9	8.96	0.22	89.13	6.20	63.22	5.86	3.72	2.41
45/55	6	5.98	0.14	87.87	6.36	40.00	5.30	2.46	2.43
45/55	3	2.98	0.072	88.21	6.59	19.85	5.50	1.31	2.28
	2A35W								
25/35	12	11.99	0.29	85.67	2.12	92.25	5.10	3.94	3.04
25/35	9	9.00	0.22	87.04	2.13	67.19	4.10	2.63	3.43
25/35	6	5.99	0.14	84.47	1.92	43.48	4.01	1.82	3.29
25/35	3	2.98	0.07	86.10	2.19	21.10	3.72	1.07	2.79
	2A45W								
35/45	12	11.99	0.29	86.46	2.10	93.84	5.78	4.60	2.61
35/45	9	8.99	0.22	88.78	2.18	67.64	5.42	3.29	2.73
35/45	6	5.99	0.14	85.08	2.04	44.39	5.67	2.36	2.54
35/45	3	2.99	0.07	85.97	2.08	20.79	5.12	1.36	2.20
35/45	3	3.06	0.07	86.06	2.15	21.95	5.78	1.39	2.20
	2A55W								
45/55	12	11.98	0.29	86.85	2.21	93.52	7.05	5.43	2.21
45/55	9	8.99	0.22	87.93	2.02	69.37	6.88	4.07	2.21
45/55	6	5.99	0.14	85.45	1.88	44.83	6.39	2.70	2.22
45/55	3	2.92	0.07	85.19	2.05	24.34	5.99	1.37	2.14
	-2A35W								
25/35	12	11.97	0.29	83.25	-2.33	102.84	5.54	4.26	2.81
25/35	9	8.98	0.22	82.23	-2.23	74.32	4.86	2.95	3.05
25/35	6	5.99	0.14	82.52	-2.22	48.64	4.60	1.96	3.05
25/35	3	2.99	0.07	81.93	-1.85	23.80	4.42	1.14	2.62
	-2A45W								
35/45	12	11.93	0.29	82.29	-2.28	105.17	6.61	4.94	2.41
35/45	9	8.98	0.22	83.25	-2.25	75.63	5.91	3.43	2.62
35/45	6	5.99	0.14	80.43	-2.23	48.83	5.87	2.39	2.51
35/45	3	2.98	0.07	81.82	-1.79	23.07	5.46	1.39	2.15

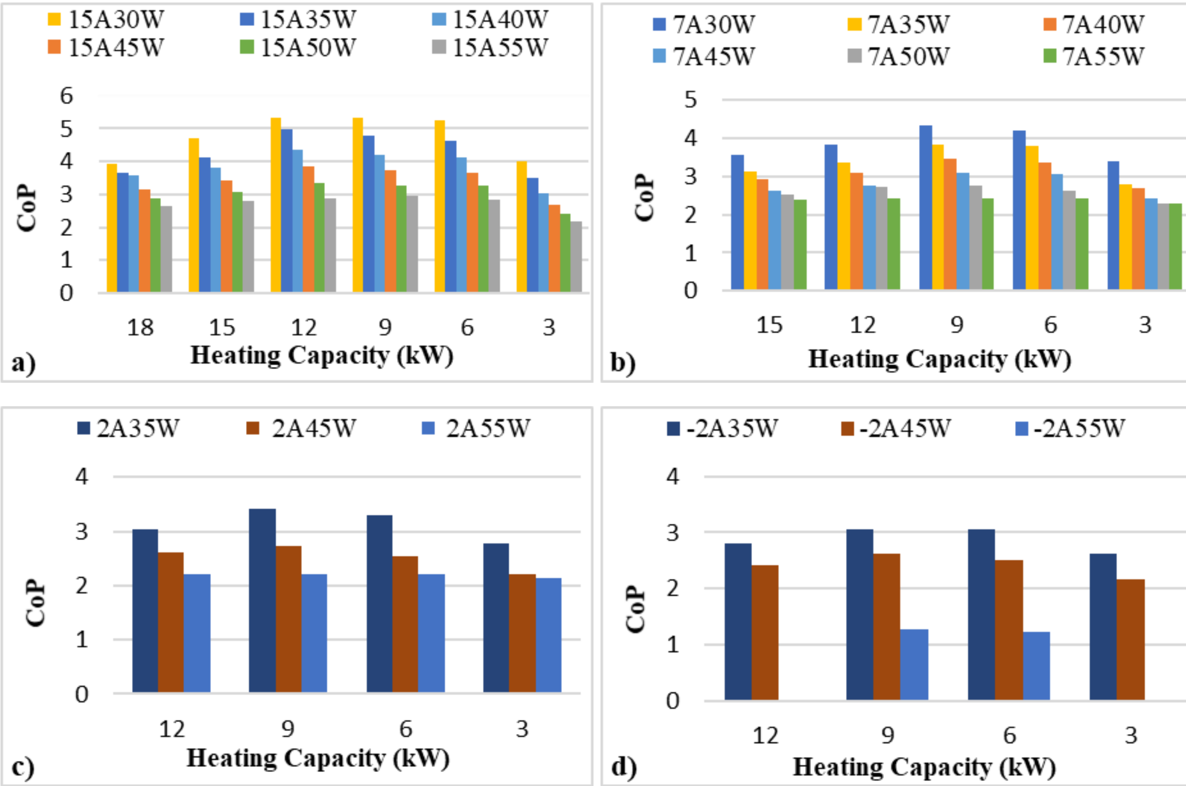


Figure 3: Heating Capacity vs. CoP at ambient temperature of a) 15 ºC, b) 7 ºC, c) 2 ºC, d) -2 ºC

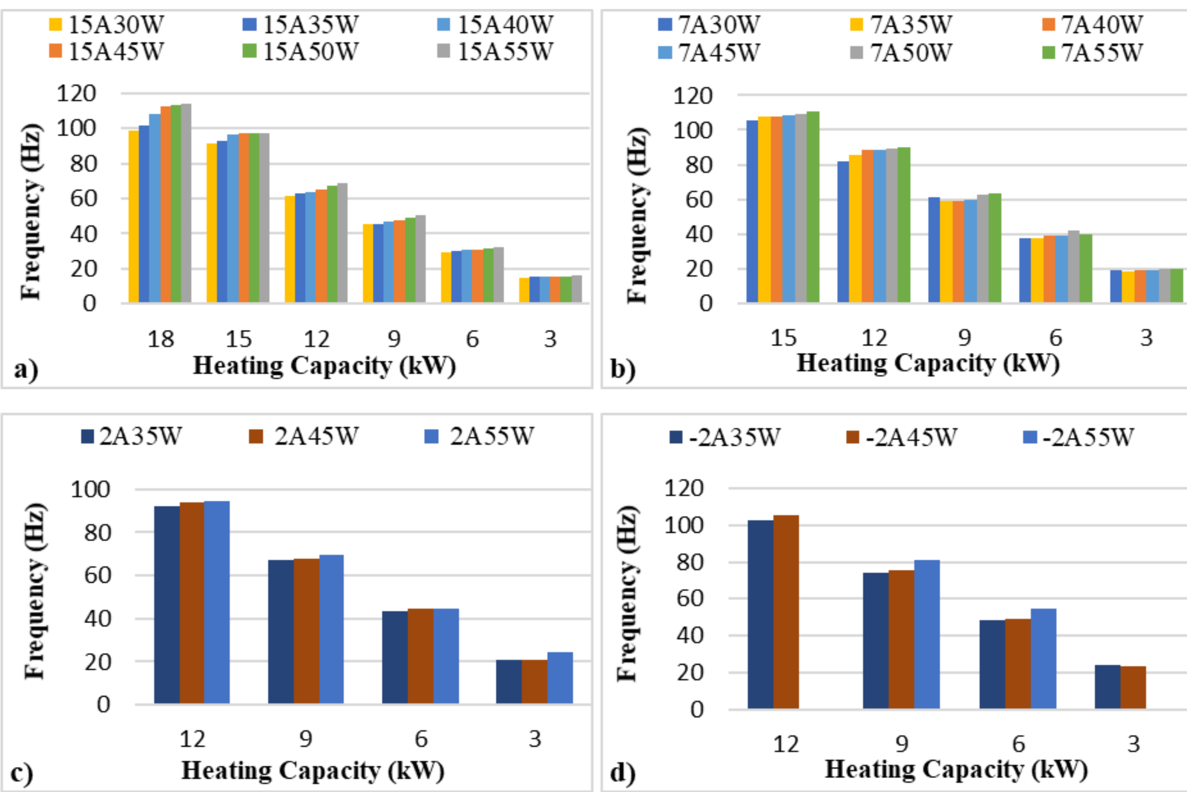


Figure 4: Heating Capacity vs. frequency at ambient temperature of a) 15 ºC, b) 7 ºC, c) 2 ºC d) -2 ºC

Table 4 shows the impact of changing delta T on the CoP and pressure ratio values for constant WST of 40 ºC, 45 ºC, 50 ºC, and 55 ºC at ambient conditions of 15 ºC. The CoP value for 18kW test with WST 40 ºC, 45 ºC, 50 ºC, and 55 ºC are 3.66 &3.55, 3.29 & 3.14, 3.05& 2.86, 2.88 & 2.62 for delta T of 20 and 10, respectively. While the pressure ratio shows the reverse pattern, where the pressure ratio is 3.61& 3.72, 3.96 &4.16, 4.31&4.53, 4.54 &4.94 for delta T of 20 and 10 respectively. At the same heating capacity, the CoP value changes according to the delta T value. Keeping delta T value smaller results in lower CoP values for the constant heating capacity and WST. The reasons for this CoP drop due to smaller delta T was higher pressure ratio (Pr) and lower isentropic efficiencies.

Table 4: Summary of test results for changing delta T values at 15 ºC

delta T=20						delta T=10					delta T=5				
HC (kW)	**P_suc(bar)**	**P_dis (bar**	**Pr**	**CoP**	**Isen. eff.**	**P_suc**	**P_dis(bar)**	**Pr**	**CoP**	**Isen eff.**	**P_suc(bar)**	**P_dis (bar**	**Pr**	**Isen eff.**	**CoP**
WST=40 ºC															
18	6.43	23.23	3.62	3.66	65.95	6.45	24.00	3.72	3.56	65.65	-	-	-	-	-
15	6.98	21.60	3.10	4.22	69.75	6.93	24.03	3.47	3.80	68.81	-	-	-	-	-
12	7.47	21.17	2.83	4.60	72.45	7.69	23.68	3.08	4.36	71.83	-	-	-	-	-
9	7.79	21.51	2.76	4.57	72.55	8.01	22.96	2.87	4.21	72.55	8.32	25.07	3.01	72.60	4.12
6	8.15	20.73	2.54	4.41	68.80	8.17	22.21	2.72	4.12	67.23	8.30	24.24	2.92	68.25	3.84
3	8.45	20.25	2.40	3.36	57.78	8.04	21.89	2.72	3.02	54.16	8.44	23.28	2.76	54.21	2.94
WST=45 ºC															
18	6.71	26.65	3.97	3.29	65.18	6.67	27.78	4.16	3.14	65.02	-	-	-	-	-
15	6.87	24.42	3.55	3.72	68.56	7.03	27.17	3.87	3.43	70.76	-	-	-	-	-
12	7.55	24.19	3.20	4.06	71.95	7.67	26.57	3.46	3.83	71.36	-	-	-	-	-
9	7.72	23.86	3.09	4.10	71.38	8.08	26.31	3.26	3.75	70.98	7.98	28.27	3.54	70.37	3.55
6	8.05	23.41	2.91	3.89	68.25	8.28	25.32	3.06	3.65	68.14	8.29	27.50	3.32	68.23	3.37
3	8.40	21.78	2.59	3.09	56.03	8.06	24.80	3.08	2.68	52.02	7.80	26.50	3.40	49.66	2.49
WST=50 ºC															
18	6.73	29.03	4.32	3.06	65.18	6.94	31.44	4.53	2.87	63.57	-	-	-	-	-
15	7.12	27.50	3.86	3.41	67.92	7.14	30.72	4.30	3.06	69.73	-	-	-	-	-
12	7.25	27.65	3.81	3.48	71.38	7.59	30.22	3.98	3.34	70.06	-	-	-	-	-
9	7.79	27.32	3.51	3.62	71.37	8.02	29.84	3.72	3.25	69.91	7.84	31.79	4.06	69.03	3.10
6	8.01	26.84	3.35	3.40	68.79	8.31	28.45	3.43	3.26	68.23	8.23	30.92	3.76	66.09	2.99
3	8.21	23.65	2.88	2.82	52.02	8.27	28.06	3.39	2.41	49.66	8.07	30.66	3.80	46.32	2.22
WST=55 ºC															
18	6.88	31.20	4.54	2.88	63.50	7.04	34.81	4.95	2.63	64.69	-	-	-	-	-
15	7.05	30.67	4.35	3.05	67.73	7.15	33.84	4.73	2.78	67.65	-	-	-	-	-
12	7.54	30.93	4.10	3.18	69.21	7.56	34.02	4.50	2.87	69.84	-	-	-	-	-
9	7.72	30.06	3.89	3.26	68.14	7.82	33.29	4.26	2.94	69.58	8.21	36.01	4.38	69.58	2.78
6	8.32	29.33	3.52	3.16	65.67	8.22	32.42	3.95	2.83	66.71	8.26	35.07	4.25	63.30	2.62
3	8.14	29.03	3.56	2.61	49.66	7.89	30.99	3.93	2.18	46.32	8.10	32.72	4.04	45.36	2.15

The main issue with the ASHP is at lower ambient conditions when the domestic heat load increases and the HP heating capacity get reduced. The variable speed compressor-based HP system could be operated at the required heating capacity to meet varying load demands without oversizing the HP system. The number of hours for specific climatic conditions at low ambient temperature is limited and hence the oversizing could be avoided. Finding the required operating speed at different ambient conditions and keeping other variables (i.e., load, WST) constant is very crucial for the operation and installation of variable speed heat pump system for domestic heat load applications at higher efficiencies. The CoP values, & the corresponding frequency for the tested ambient conditions at WST of 35 ºC is shown in Fig. 5(a, b). The frequency of operation for 12kW, 9kW,6kW, 3kW at 2 ºC ambient temperature conditions, at WST of 35 ºC was 92.24 Hz, 67.18Hz, 43.47 Hz, 21.1 Hz with absolute percentage difference of 53.73%, 11.96%, 27.55%, 64.85% to that of 60Hz and the corresponding impact on CoP values could be observed. The CoP values for higher WST of 45 ºC & 55 ºC is shown in Fig.6 (a, b).

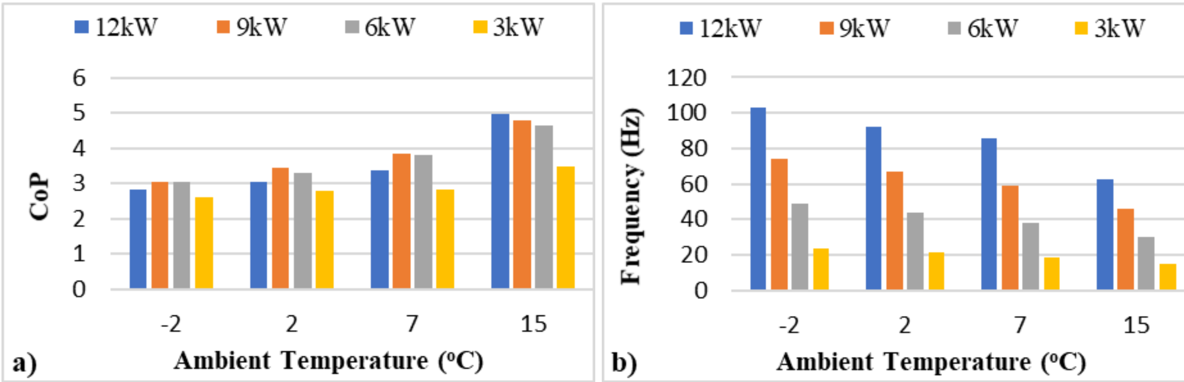


Figure 5: Ambient temperature vs. a) CoP, b) frequency at low water supply temperature (WST) of 35 ºC

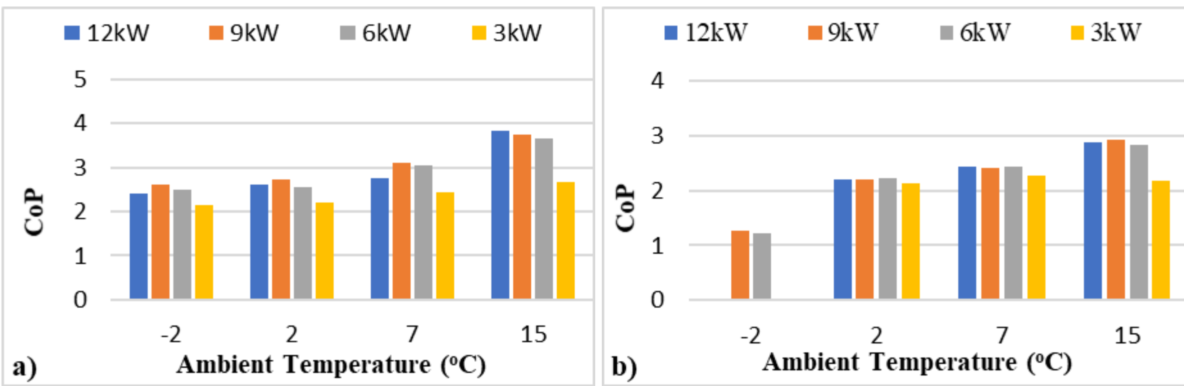


Figure 6: Ambient temperature vs. CoP at WST of a) 45 ºC, b) 55 ºC

4. CONCLUSION

The variable speed compressor based ASHP experimental results are presented in this paper over a range of operating conditions and heating capacities for the low to higher heat supply temperature. The aim of the experimental development and testing was to study the HP domestic retrofit and energy savings with variable speed compressor-based HP system at different heat supply temperature. The results for the developed ASHP system under controlled laboratory conditions provide a strong base for the evaluation and predictions of the system annual CoP prior to the field installations into different housing stock & climatic conditions. It was concluded that the three parameters namely ambient temperature, WST and operating frequencies strongly impact the HP performance.

NONMENCLATURE

ASHP	air-source heat pump
CoP	coefficient of performance (-)
CO_2	Carbon di-oxide (-)
delta T	difference between supplied and entering water temperature
EWT	entering water temperature (ºC
WST	water supply temperature (ºC)
P	power (kW)
Pr	pressure ratio (-)
PID	Proportional Integral Derivative

Q	heating load(kW)
RPM	revolution per minute (-)
HC	heating capacity (kW)
HD	Heating demand (Kw)
Φ	Frequency (Hz)

Subscripts

a	ambient
Cp	specific heat capacity
w	water
r	refrigerant

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